Bonnie S. Hautamaki, Timothy Bagnall, and Ronald L. Small

Human Interface Evaluation Methods for Submarine Combat Systems

ABSTRACT

This paper describes research done by Micro Analysis & Design, Inc. (MA&D) for the Naval Sea Systems Command (NAVSEA) and the Naval Undersea Warfare Center (NUWC) under the Small Business Innovation Research (SBIR) program. We developed objective tools, metrics, and a methodology for improving submarine combat system operator interfaces. Our methodology included understanding the domain, developing human performance models of operator tasks and decisions, and then devising solutions for specific challenges. In this research, MA&D developed a task-network model of the submarine combat system in order to compare operator performance in the baseline model to performance with the enhanced system, to determine whether the proposed modifications will yield an overall improvement in system performance. Though the focus of the current research is toward the Combat System operator, all work has been performed with the decision maker in mind. This research, then, will provide groundwork and contributions toward understanding and improving the decisions made at the command level. Furthermore, findings from the operator task-network model have the potential to apply toward system, employment, and training improvements.

INTRODUCTION

The submarine Combat Control System (CCS) is one of the most challenging work environments in the Navy. The CCS is designed to help the combat system (CS) operator form a picture of the surrounding marine environment with an emphasis on surface and subsurface vessel locations. Conditions of the environment and imperfections of sensing technology pose a compounded challenge for the CS operator. Environmental challenges include: the physics of underwater acoustics, underwater hazards, the necessity to work as quickly as possible, severe consequences if the job is not done properly, and working in a threat situation. Data-related challenges include: working with massive quantities of sensor data, the inherent uncertainty in sensor data, the possibility that any contact could be hostile, and the requirement to quickly and accurately process numerous alerts of varying levels of severity. The CS operator, then, must sort through this mass of data and provide the relevant information up the chain to support decision making.

Because a sub crew essentially operates "blind," the primary method of sensing their environment is to listen to acoustic signals by means of passive sonar. There are listening devices – sonar arrays – located in the bow, along the length of the sub, and even trailing behind the sub in the form of a towed array. By listening to various signals over time, the crew forms a picture of the surrounding vessels. They form this picture by processing the acoustic signals that have been initially filtered by the members of the sonar party. The acoustic signals give clues

about the type of ship and its approximate bearing from ownship. Since these signals can behave in unpredictable ways, the CS operator has a rather formidable job.

The sonar party passes detected information to the CS operators so that they can track contacts over time and try to ascertain their range, bearing, course, and speed. The combat system is comprised of sophisticated tools to help operators perform target motion analysis (TMA) on contacts of interest. The tools available to the CS operator include a variety of automatic algorithms, as well as manual tools for performing TMA. It is up to the individual operator as to which automated or manual approaches he will use to obtain a TMA solution; each operator may use a different set of strategies, techniques, and methods. Each method contains a set of inherent assumptions (e.g., constant target velocity, maneuvering target, direct path sound propagation, etc.), and it is up to the operator to determine which assumptions apply to the situation at hand. This results in a variety of methods in use for each mission and environmental situation. In determining a solution, then, the CS operator will use a combination of basic assumptions and observations to estimate a contact's bearing course, range and speed, and employ CCS tools to determine whether his solution fits the observed data. Because of the inherent uncertainty in the data and the complexity of the task, determining a correct TMA solution for a contact can be very difficult, and is subject to error. This is especially true when there are many contacts and little time to perform TMA on each contact. Typically, in such a situation, a triage approach works: CS operators will perform TMA on a contact just enough to ascertain whether it is a potential threat to ownship.

The underlying problem of the CCS is that due to the inherent uncertainty of the operating environment, there is significant opportunity for error. The CCS is designed to help the operator form a tactical picture of the surrounding surface and subsurface vessels, as accurately as possible, given the current ocean conditions. Accompanying the CCS, there has traditionally been a plethora of alerts that would notify the CS operator of track conditions which violate expected operating ranges. Although well intended, when these alerts were first introduced into the CCS, they indicated isolated incidents that often did not convey to the CS operator the severity of the situation as a whole. A CS operator would receive several individual alerts for a contact, each carrying little weight when considered on its own; however, when considered collectively, this group of alerts could indicate a critical situation. This is a case when the whole is greater than the sum of its parts. Improvements to the CCS over the years have incorporated this concept of amassing disjointed but related alert information, yet, there is still room for improvement. One particular shortcoming of the Alert Manager window on the Tactical Control and Weapons Control interface is the subtle method by which it presents alerts. If an operator is not looking directly at the Alert Manager window, he has no way of knowing how many safety alerts exist. There have been recorded instances of operators being so preoccupied with an ongoing task that they fail to notice a number of safety alerts that could shed light onto the very problem that they are trying to solve. Or, in the case where an operator is cognizant of how many alerts exist, the organization of the alerts does not allow the operator to easily grasp an accurate picture of the current situation. The current organization of the safety alerts is by order of occurrence or contact number, which provides little utility in terms of determining which alerts are most severe. Some operators have requested that the safety alerts also be organized by impending danger levels so that decision makers can quickly grasp which source of danger needs to be dealt with first.

With the above background in mind, we next highlight our approach, the tasks we accomplished, and the ensuing results.

MA&D's APPROACH

The challenge, then, for CCS designers, developers, and engineers, is to produce a system that helps the CS operators without increasing the system complexity. It is a well known fact that the operator is the primary driver of the performance of the combat control system. Since human error is the most common root cause of submarine combat system failures (i.e., bad TMA solutions), a prevalent approach for incremental improvements in the CCS has been to (a) consult with domain experts to determine what caused historical errors, and (b) provide a system upgrade for each root problem that caused the individual error. The drawback with this approach is that the sum of the individual upgrades does not necessarily create a better overall system. And at present, there is a marked absence of tools to aid in assessing the impact of potential system upgrades on operator performance. There is also an absence of information as to the extent to which operators are using currently available CCS tools. Since operators are the primary driver of system performance, it is important to understand how well the operators are using the current system. In addition, it would be valuable to have a predictive tool to assess the impact of potential upgrades, since the cost of proceeding with the actual development and laboratory testing of a particular upgrade is expensive, both in terms of time and money.

What is needed is an objective process to efficiently and effectively select system upgrades for incorporation into the existing operational improvement program. The Phase I project that MA&D accomplished was a brief exemplar of how the Navy might wish to undertake submarine CCS upgrades in the future. The key to MA&D's human-systems integration (HSI) process is to model, in a realistic setting, the human operators in the system. This requires a thorough understanding of the operators' goals, tasks, thought processes, decisions, and actions. For a submarine combat system, it is unrealistic to develop a comprehensive human performance model within the constraints of a Phase I SBIR project. Therefore, we modeled appropriate "slices" within a challenging scenario. This scenario was developed in cooperation with our customer, the Navy's Sub School, and three retired sub skippers.

In concert with the scenario, we created a task-network model of the CCS, focusing on the CS operator. This task-network model can be the basis for a tool to aid in the selection of system upgrades. In addition to the task-network model, MA&D also designed a tool to monitor system and environmental hazards, and appropriately alert the operator. We named this tool the "Hazard Monitor & Intelligent Alerting System" (HMIAS). HMIAS is, in part, an investigative method for understanding the root causes of human error and for preventing them from occurring.

Even though human error is the most common cause for system failures, inadequate system design can also lead the operator down the path to error. Stress is another common contributor to operator error, particularly in military environments. MA&D's primary expertise is in re-engineering systems to improve operator performance, taking into account the working environment and human stressors such as a combat situation or fatigue. To re-engineer a system, we typically model the baseline system and its human operators, and use objective metrics (e.g., task timing, accuracy, errors, required training level) to compare the baseline to proposed improvements while those improvements are still in the design stage. Our modeling approach

helps to identify potential enhancements that could provide the greatest overall system improvement, so that the fleet can focus resources on the most effective system upgrades.

Metrics

We began this study with a broad selection of metrics, gathered from the HSI community in multiple domains. A suitable set of metrics is essential for comparing the new, upgraded system to the current, baseline system. When metrics are available for system requirements, this also provides the opportunity to compare operator performance from the model to system requirements. It should be noted that the new or upgraded system need not show improvement in every category of metric or performance; however, there should be a clear indication of overall improvement. The following list is a collection of suitable metrics for a study of CS operator performance.

- Number of errors
- Number of missed alerts
- Number of false alarms
- Task accuracy
- Task reaction time
- Training time required for task
- Situation Awareness (SA)
- Confidence in solution
- Workload in Visual, Audio, Cognitive, and Psychomotor channels (VACP)

In order to determine the best set of metrics to use for this study, it was necessary to take a closer look at the situation to be modeled. Thus we developed a realistic, unclassified scenario to set the stage for modeling operator actions in the CCS.

Scenario

After visiting Sub School, NUWC, and working with our Navy customers, we developed a realistic, yet unclassified, scenario comprised of four main elements: (1) anti-submarine warfare, (2) anti-surface warfare, (3) going to periscope depth, and (4) transit through a strait.

The resulting scenario is depicted in Figure 1 and described in the text below. This scenario was then used as a basis for creating the task-network model. It should be noted that time stamps are indicated by $[T_i]$. The world and ownship states at each T_i are not included here to save space.
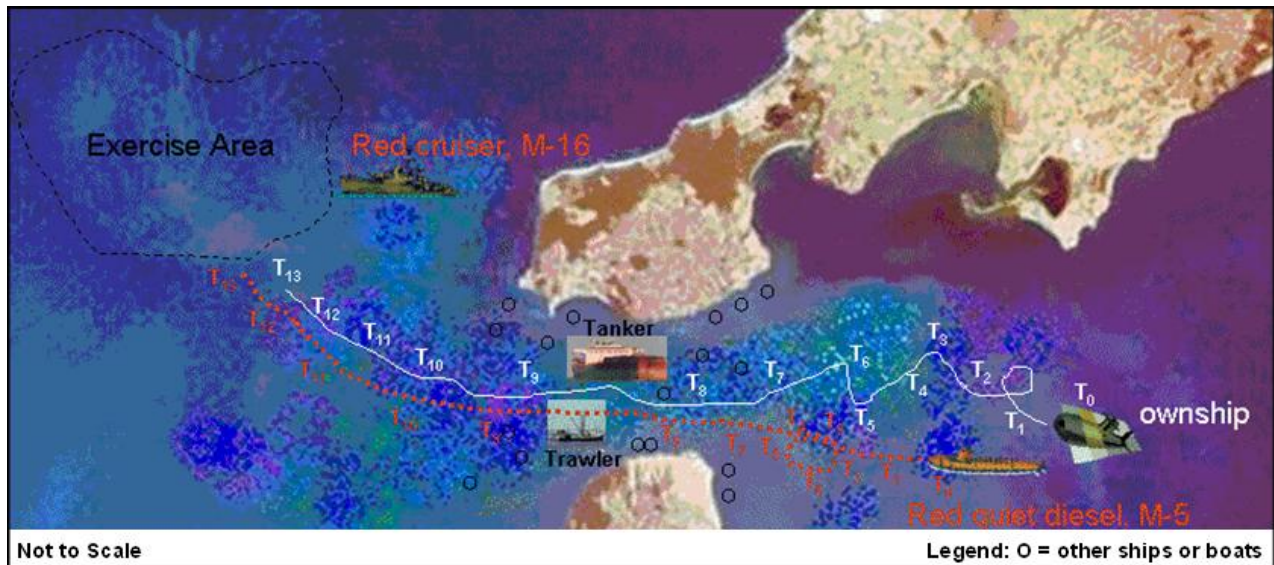

Figure 1. Scenario graphic.

We are in the *USS Texas*, a modern attack submarine. Our mission is to track an unfriendly quiet diesel submarine through the *Blue Straits* in order to determine their procedures for such a transit (i.e., course, speed, depth, maneuvers, track taken, etc.). It is assumed that the unfriendly is proceeding to an area to observe an allied exercise. A mission requirement is to remain undetected. During the strait transit, we expect to encounter numerous vessels including deep-draft tankers and fishing trawlers, as well as other commercial vessels. The slice of the scenario that we focus on in the remainder of this paper is our encounter with a deep-draft tanker; this occurs as we are tracking the quiet diesel through the strait.

Mission Metrics

After considering the scenario, the information that would be available to the CS operator, and what would be a realistic yet manageable scope for a Phase I SBIR, we selected a subset of metrics, listed in Table 1, on which we could evaluate performance in the baseline model compared to a model that reflects enhancements to the alerting system.

Related Mission Metric	How measured
Closest point of approach of hazards	Miss distances in 3D to other ships or obstacles
Area of uncertainty (AOU) overlap	Time and amount of overlapping AOUs with hazards
Abrupt maneuvering	Number and suddenness of maneuvers to avoid hazards
Proper track position	3D distance from desired track (especially in relation to contact of interest)

Table 1. Mission-related metrics.

Model

The next step was to develop a task-network model to simulate several human operators in a *Virginia* class submarine control room. The model allows for the analysis of human performance and the flow of information in the CCS. The specific human operators selected were personnel in the sonar party, fire control party, and the Officer of the Deck. The sonar party includes three sonar technicians and a sonar supervisor. The fire control party includes two CS operators and a CS supervisor. The main focus of the model was on the CS operator. We present a brief description of the simulated portion of the scenario below.

The simulation commences three hours and fifty minutes into the scenario, where ownship, the *USS Texas*, is transiting the *Blue Straits* and tracking a quiet diesel submarine. We chose to simulate this portion of the scenario because it presents several interesting challenges to the control room. Heavy commercial and civilian activity adds more workload to the sonar and fire control parties, and high background noise levels further mask the subtle sounds of the quiet diesel submarine. Twenty minutes later, the simulation concludes, when a controlled close aboard encounter with a deep-draft tanker requires an evasive maneuver.

Figure 2 shows the tasks modeled for the CS operator. In summary, the CS operator's job is a recurring task of continuously hunting for the best system solution for contacts using TMA.
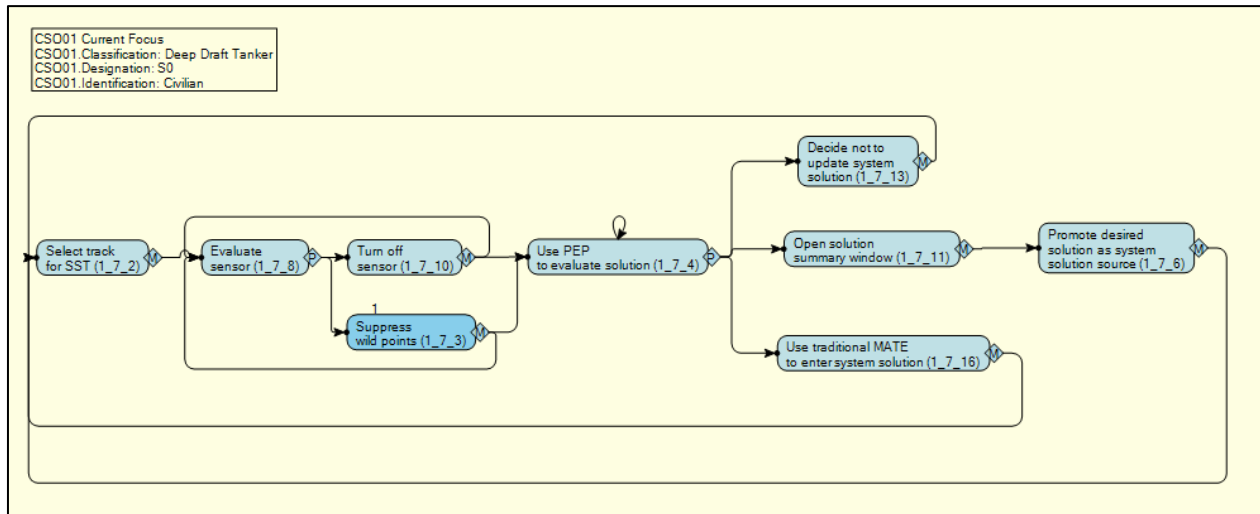
CSO01 Current Focus
CSO01.Classification: Deep Draft Tanker
CSO01.Designation: S0
CSO01.Identification: Civilian

Decide not to update system solution (1_7_13)

Select track for SST (1_7_2)

Evaluate sensor (1_7_8)

Turn off sensor (1_7_10)

Use PEP to evaluate solution (1_7_4)

Open solution summary window (1_7_11)

Promote desired solution as system solution source (1_7_6)

1 Suppress wild points (1_7_3)

Use traditional MATE to enter system solution (1_7_16)

Figure 2. Combat System operator network.

The cycle for the CS operator begins with "Select track for SST" (Screen Selected Target), whereby he selects a track, or existing contact, for further analysis. In some cases the CS supervisor will assign an operator to exclusively monitor one track. At other times the operator will be responsible for several tracks at a time. Next, the CS operator will evaluate the sensors that hold information about the selected track. After evaluating the sensors, the CS operator will use the Parameter Evaluation Plot (PEP) display to evaluate each of the automated solutions. After evaluating the automated solutions, the CS operator will perform one of three tasks: (a) keep the current system solution on that track, (b) promote a better solution, or (c) employ the traditional MATE (manual adaptive TMA evaluator) system to enter a manual solution.

The scenario we modeled considers the time elapsed since the CS operator entered a manual solution. If the operator neglects to update a manual solution, his tactical picture can quickly become incorrect, and a hazardous situation is more likely to occur.

Animation
To augment the task-network model, we developed two types of animation to provide increased visualization and better understanding of the events in the model. We developed animation of (1) the information flow in the control room (e.g., conversation and alerts), and (2) areas of uncertainty for ownship and the surrounding vessels in the model. Both types of animation have yielded positive feedback for increased understanding of the events in the CCS, and have potential for CCS training and familiarization.

Hazard Monitor & Intelligent Alerting System
An important aspect of human performance modeling and simulation is accounting for human error. Because CS operator errors do occur, we proposed using our HMIAS technology to monitor for, prevent, trap, and capture operator errors. The emphasis of HMIAS is on preventing the negative consequences of errors. A generic Hazard Network is shown in Figure 3.
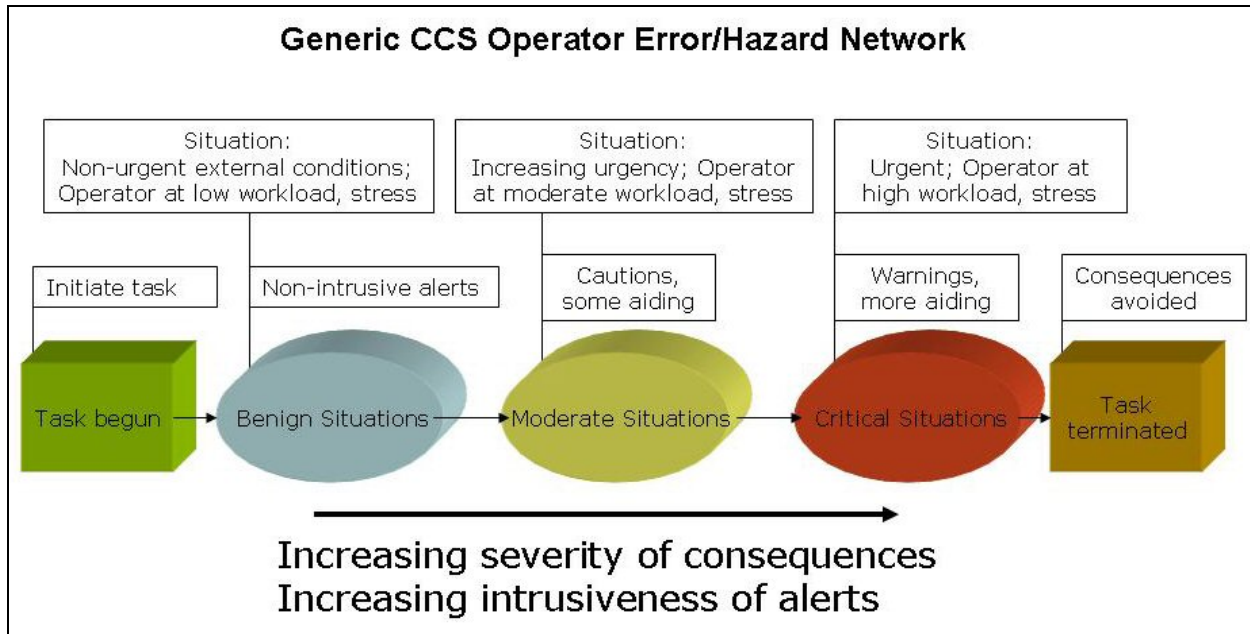
Figure 3. Hazard Network.

HMIAS does not simply monitor system states for hazards, but it also alerts the human operators to those hazards in a timely, context sensitive, and multi-modal manner. As events in this diagram proceed from left to right, we see an increase in the severity of consequences, and also in the intrusiveness of alerts. For example, an initial alert could be presented in the form of text on the operators' screen. If this alert is not acknowledged in sufficient time, and the conditions persist or worsen, the alert would be promoted to flashing text. The next alert level would include an audible alarm, followed by the addition of verbal instructions if necessary.

Results

Our model compared CS operator performance using a current CCS to one enhanced by HMIAS during the encounter with a deep-draft tanker in the strait. We devised human performance and mission-relevant metrics for the comparison. Results, shown in Table 2, indicate that HMIAS could be a useful CCS enhancement. Without HMIAS, ownship passes within 1000 yards of the deep-draft tanker, and requires a 90 degree evasive maneuver to avoid the hazard. With HMIAS, the closest point of approach to the tanker hazard is twice the distance – 2000 yards, and the evasive maneuver results in a much smaller angle off the desired track – just 30 degrees.

Mission Performance Metric	Without HMIAS (Baseline)	With HMIAS
Closest point of approach to deep-draft tanker hazard	1000 yards (approx. 0.5 nm)	2000 yards (approx. 1.0 nm)
Distance to hostile submarine after avoiding tanker (goal is 4nm)	4.71 nm (approx. 9540 yards)	4.14 nm (approx. 8385 yards)
Angle off desired track after avoiding tanker	90 degrees	30 degrees

Table 2. Baseline CCS vs. notional HMIAS-enhanced results.

CONCLUSION

This research, focused on the CS operator, provides the groundwork toward understanding and improving the decisions made at the command level. Findings from the operator task-network model have the potential to apply toward system, employment, and training improvements.

The primary benefit of our research has been the development of objective tools, metrics, and a methodology for improving submarine combat system operator interfaces. These tools, metrics, and the related methodology also apply to other complex control systems, such as those found in commercial power and chemical plants, and in other military systems. MA&D engineers have used such tools over many years in support of a wide array of customers who operate in varied domains. There is potential, again, to take the methodology and tools from this research and employ them in other branches of the military or in industry.

We also addressed, as part of this research, the prevention of errors and their consequences with the HMIAS application. We assert that HMIAS can help the CS operator by capturing his attention more quickly than might occur with the current CCS alerts. The HMIAS alerts are more context sensitive than the current alerts, and are harder to miss (or ignore) because of their increasing level of intrusiveness. In addition, HMIAS can help increase awareness and disseminate critical information to all members of the tracking party in a timely, context sensitive manner which takes into account the appropriate interface method(s) for the current situation.

Next Steps

MA&D recently submitted a Phase II proposal to continue this research via the following steps: (1) further develop the task-network model, (2) develop a prototype of the HMIAS application, (3) identify display improvements for CCS user interfaces, and (4) pursue the development of innovative displays related to uncertainty. There are also opportunities to work with the Tactical Control Development Working Group and the related Advanced Processor Build (APB) development at both the working group level and with NUWC. We will work with NUWC to identify possible products from this research to target toward the APB step process; the HMIAS application, in particular, shows excellent potential for such a transition.

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Bonnie S. Hautamaki, CPE *is a Staff Human Factors Engineer at Micro Analysis & Design in Boulder, Colorado. She earned an MS in Industrial Engineering and Bachelor of Mathematics from the University of Minnesota, and the CPE designation from the Board of Certification in Professional Ergonomics. Her interests are user interface design and evaluation, the usability of words, GUIs, products, and processes. Prior to her work in modeling military environments at MA&D, Ms. Hautamaki was formerly a systems analyst, usability engineer, author of online help, and user interface designer.*

Timothy Bagnall *is a Systems Engineer at Micro Analysis & Design in Boulder, Colorado. He earned a BS degree in Systems Engineering from the University of Virginia. Mr. Bagnall has five years of experience in simulation, human systems integration, and in human factors engineering. His experience includes design, specification, development, testing and integration of many government human performance models and various interface displays and workstations.*

Ronald L. Small *is a Principal Engineer at Micro Analysis & Design. He earned an MS in Computer Engineering from the Air Force Institute of Technology and a BS in Mathematics from the US Air Force Academy. He has 33 years of aviation human factors R&D experience which he has begun to apply to the submarine command center environment while at MA&D. Mr. Small has authored numerous publications on the subject of human-centered system design in the aviation field and in other domains.*